Sub–degree anisotropy observations:
ground–based, balloon–borne and space experiments.

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ABSTRACT – Extensive, accurate imaging of the Cosmic Background Radiation temperature anisotropy at sub–degree angular resolution is widely recognized as one of the most crucial goals for cosmology and astroparticle physics in the next decade. We review the scientific case for such measurements in relation with sky coverage, attainable sensitivity, confusing foreground radiation components, and experimental strategies. Although ground–based and balloon–borne experiments will provide valuable results, only a well–designed, far–Earth orbit space mission covering a wide spectral range and a significant part of all the sky will provide decisive answers on the mechanism of structure formation.

1. INTRODUCTION

A strong effort in observational cosmology will be dedicated in the next years to measurements of Cosmic Background Radiation (CBR) anisotropies on scales from several arcminutes to few degrees and on regions of the sky as large as possible, to obtain the highly accurate statistics required to answer fundamental questions about the origin of structures in the universe. These observations would also have an enormous impact on high–energy physics because of the linkage between studies on primordial universe and those on particle physics.

As shown by many authors, the CBR anisotropy is the result of many physical processes working on quite different scales and cosmological epochs. Thus the expected anisotropy is sensitive to a number of initial conditions and physical processes, such as the possible existence of field defects (walls, cosmic strings, monopoles and textures),

the slope and amplitude of primordial energy density and gravitational wave fluctuations, the Hubble constant, the cosmological constant, the baryon density, the ionization history *etc.* (Crittenden et al. 1993, Bond et al. 1993, Kamionkowsky et al. 1994).

Temperature fluctuations are usually decomposed in spherical harmonics

$$\Delta T/T\,(\theta,\phi) \equiv \sum_{lm} a_{lm} Y_{lm}\,(\theta,\phi)\,, \tag{1}$$

with rotational symmetric quantity $a_l^2 \equiv \langle \mid a_{lm} \mid^2 \rangle$. With this notation the all–sky variance is given by

$$\langle (\Delta T/T)^2 \rangle = \sum_l \frac{2l+1}{4\pi} a_l^2 W_l, \tag{2}$$

where W_l is a window function depending on the characteristics of the experiment.

One of the most relevant open questions of the theory of structure formation concerns the statistics – gaussian or non–gaussian – of primordial anisotropies.

Density fluctuations generated by topological defects are intrinsically non–gaussian and the mass distribution is rather sporadic. These properties have been used in the attempt of explaining the strong clustering of galaxies as compared to the mass distribution within an Einstein–de Sitter universe. Many authors pointed out that these models are severely constrained by the $COBE$–DMR data, but still viable (Turok and Spergel 1990; Bennet, Stebbins and Bouchet 1992; Ue–Li Pe and Spergel 1993). The most effective way to discriminate between non–gaussian and gaussian primordial perturbations is the statistical analysis of the distributions of $\Delta T/T$ on angular scales ranging from several arcminutes to one degree (Perivolaropoulos 1994; Coulson et al. 1994).

Cosmic strings are the most investigated case of topological defects and many authors have produced detailed predictions. The $COBE$–DMR data do not exclude string models (see e.g., Bennett, Stebbins & Bouchet, 1992). On the other hand, mapping the distribution of the CBR temperature fluctuations in many thousands adjacent pixels with angular resolution of $\sim 15'$ would enable a clear discrimination between gaussian and non–gaussian primordial perturbations, if global uncertainties of at least 5×10^{-6} in $\Delta T/T$ per single pixel can be achieved (Hara et al. 1993).

Coulson et al. (1994) have produced 30×30 degrees simulated maps of CBR temperature fluctuations generated by cosmic defects. All maps have been smoothed with a gaussian window of full-width half–maximum (FWHM) $\sim 1^\circ$. It is apparent that the differences among the case of strings, monopoles and textures are only appreciable for experiments designed to image the sky at high sensitivity and with large sky coverage.

Curvature (adiabatic) or isocurvature fluctuations might have been generated at very early epochs. Models based on the generation of gaussian, adiabatic fluctuations via inflation have been extensively studied. The standard inflation theory predicts that the coefficients a_{lm} and the rms fluctuations are independent gaussian random variables.

The theoretical predictions yield estimates of $\langle a_l^2 \rangle_{ens}$, the average over an ensemble of universes (White et al. 1993). As a consequence there is an inherent uncertainty in measuring the radiation power spectrum a_l^2 even in the case of all–sky surveys, since we are observing the fluctuation distribution from only one point in a unique universe (cosmic variance). For instance when we fix the normalization of the power spectra by fitting the predicted $\Delta T/T$ to the COBE measurements we are left with an uncertainty due to cosmic variance of $\approx 20\%$ (White et al. 1993).

Small–scale anisotropies are dominated by higher modes, which have more degrees of freedom and smaller *cosmic* uncertainty, because a_l^2 is χ^2- distributed with $2l+1$ degrees of freedom (White, Krauss and Silk, 1993). An additional source of uncertainty in reconstructing the radiation power spectrum is connected to the sky coverage. Large sky coverage at intermediate and small angular resolution producing many thousands of pixels would squeeze the statistical errors to few percent of the signal. Scott et al. (1994) showed that the sample variance is approximately related to the cosmic variance by

$$\sigma_{sam}^2 \simeq (4\pi/A)\sigma_{cos}^2, \tag{3}$$

where A is the solid angle covered by the observations. Taking into account the dependence of the cosmic variance on the pixel size (determined by the beam angular resolution, θ_{beam}) it can be shown that the relative uncertainty due to the sample variance is $\sim (2/N_{pix})^{1/2}$, where $N_{pix} \approx \frac{A}{\theta_{beam}^2}$ is the number of pixels in the observed sky area. For instance, with $\sim$ 10,000 pixels available (a conservative estimate for a well designed space experiment) the relative uncertainty in the coefficients a_l^2 is reduced to a few percent at high confidence level (see Bond et al. 1993). As for the expected level of the CBR fluctuations on half–degree angular scale, both theoretical models and available observations predict values of $\Delta T/T \sim$few$\times 10^{-5}$ (see e.g. Smoot et al. 1992; Gundersen et al. 1993; Cheng et al. 1994; Bond et al. 1993; Sugiyama et al. 1993).

Imaging the CBR fluctuations with high precision and accuracy over a *large* portion ($\sim$ 1/4–1/3) of the sky at angular resolutions ranging from *10' to 30'* will not only discriminate between gaussian and non–gaussian initial perturbations, but will also produce fundamental observations to investigate the history of the universe.

Recently Bond et al. (1993) examined to what extent the initial conditions and the evolution of the perturbations in the universe can be inferred from the analysis of CBR anisotropy. They showed that the determination of the CBR anisotropy on angular scales from about 10' to few degrees would afford important information on a combination of basic parameters such as the power law index n_s of the amplitude of the energy density fluctuations, the ratio r of the tensor–to–scalar quadrupole, the Hubble constant, the cosmological constant and the epoch of the reionization. The reconstruction of the radiation power spectrum together with independent observations on large–scale structures, on the Hubble and cosmological constants and the thermal

history of the universe, would allow to test the inflation hypothesis.

It is expected that in the next decade degree and sub–degree anisotropy measurements will be performed with a variety of techniques and experimental designs. The main focus of this paper is to compare the relative merits and challenges of experiments designed to be performed from ground, balloon and space. In §2 we will discuss the problems posed by foreground emissions. In §3 we briefly address the main experimental approaches. After a discussion in §4 we present our conclusions in §5.

2. FOREGROUND EMISSIONS

The foreground radiations hampering the measurements of the CBR anisotropy are the galactic emission and the integrated emission from extragalactic unresolved sources. Atmospheric emission is an additional foreground source for ground–based and balloon–borne observations. In order to greatly reduce the uncertainties in observing CBR anisotropy one has to accurately subtract the contributions by unwanted foreground radiations.

Instrumental sensitivities at few μK level with reasonable integration time are now reachable. As for the galactic contribution, the limiting factor in interpreting the measurements is our knowledge of galactic emission even in the case of observations with intrinsic sensitivities at the level of several tens of μK (the *COBE*–DMR sensitivity; see Bennett et al. 1992; 1994).

2.1 Atmospheric emission

Atmospheric emission is the largest unwanted emission for ground–based and balloon–borne experiments.

For 40 km altitude balloon flights the expected atmospheric continuum emission at the zenith yields an antenna temperature of a few mK. On the other hand, with the large bandwidths used by bolometric techniques the line emission can give an important additional contribution to the atmospheric signal. As a result, the atmospheric subtraction is not so trivial. For instance for the TopHat experiment the chopping technique has been designed for monitoring the time–variable atmospheric noise (Cheng 1994).

For ground–based experiments much depends on frequencies and locations. To be specific let us refer to the Tenerife site and to the Amundsen–Scott South Pole station.

At Tenerife (Canary Islands) will be located the Very Small Array (Lasenby et al. 1994) experiment, an interferometer that will map the CBR. The site is 2.4 km above sea level. At this altitude and with water vapor column of 2 mm (typical value for that site) the antenna temperature of the atmosphere is $T_A \sim 4.7\ K$ and $T_A \sim 8.7\ K$ at $\nu = 28$ GHz and $\nu = 38$ GHz respectively. These antenna temperatures are rather similar to the antenna temperature expected at Cambridge at 15 GHz, the operative

frequency of the prototype Cambridge Anisotropy Telescope (CAT). CAT observations seem to be unaffected by atmospheric noise down to $\sim 2 \times 10^{-5}$ (Efstathiou, private communication; Lasenby et al. 1994), demonstrating that the atmosphere on arcmin scales does not produce noise at levels larger than $4 \times 10^{-6}\ T_A$. Even assuming than on larger scales the atmospheric fluctuations do not increase, we would need to lower the effects of atmospheric noise at least by a factor ~ 10 to get the precision required to disantangle the contribution of the galactic foregrounds. The possibility of obtaining such a level of subtraction of the atmospheric emission is still unsettled. For instance, in the case of the ACME experiment at South Pole (possibly the best site in terms of atmospheric emission and stability) at frequencies around 30 GHz, the main limitation is due to the atmospheric noise (Gaier et al. 1992). After removing $\sim 70\%$ of the data for *bad* weather a limit of $\Delta T/T \leq 1.4 \times 10^{-5}$ was found. Since the atmospheric emission amounts to about 4.6 K, with only 0.15 K contributed by water vapor (0.5 mm H_2O column), the atmospheric noise should be at a level of $3 \times 10^{-6}\ T_A$.

In addition to water vapor fluctuations, pressure gradients in the observed sky patches are likely to induce significant variations of the O_2 emission, as direct measurements from the South Pole site have shown (Meinhold & Lubin, 1991; Meinhold et al 1993; Bersanelli et al 1994).

In conclusion it may be a very hard test for ground–based experiments to remove atmospheric noise to the levels required to accurately subtract the galactic foregrounds on large portions of the sky. Even for balloon–borne experiments this issue proves not trivial.

2.2 Galactic emissions

The galactic radiation at frequencies below ~ 20 GHz is dominated by the synchrotron emission which approximately follows a power law in frequency

$$I_{sync} \propto \nu^{-\beta} \tag{4}$$

with $\beta \sim 0.7 - 0.9$ and a possible steepening towards higher frequencies (see Bennett et al. 1992). All–sky maps at low frequencies are available at 408 and 1420 MHz (Haslam et al. 1970; Haslam et al. 1974; Haslam et al. 1982; Reich 1982; Reich & Reich 1986, 1988). An extensive map at 19 GHz has been obtained by Boughn et al. (1992). Complementary studies on polarization, magnetic fields and electron energy distributions have been performed. As a result the contribution of the synchrotron emission is rather well understood, although much work still has to be done. A significant improvement is expected in the near future as measurements currently in progress will yield multi-frequency galactic maps over lage sky areas (e.g. De Amici et al. 1994).

Our knowledge of the free–free emission, the other galactic foreground at radio wavelengths, is at the moment rather poor. However, the free-free emission seems to be

concentrated towards the galactic plane (Bennett et al., 1992), so that its importance is partially reduced at high glactic latitudes. It would significantly dominate on the synchrotron only at frequencies $\nu \gtrsim 100$ GHz due to its frequency dependence ($I_{ff} \propto \nu^{-\alpha}$, with $\alpha \sim 0.1$). However, at these frequencies the galactic dust emission already dominates. As a consequence no direct maps of the free–free emission are available and only indirect reconstructions have been produced by subtracting the synchrotron component from radio maps (Bennett et al 1992; 1994). Additional indirect indications on free-free emission come from the relationship of the free–free emission with other probes of the warm ionized medium such as the H_α and N^+ emissions (Reynolds 1992; Wright et al. 1991; Bennett et al. 1992; Bennett et al. 1993).

Dust dominates the galactic emission at frequencies $\nu \gtrsim$ 90–100 GHz. Dust emission depends on the Interstellar Radiation Field, gas chemical composition, dust to gas ratio, and grain composition, dimension and structure. Thus variations from place to place are expected. Relevant information comes from the IRAS 60 and 100 μm surveys with few arcminutes of resolution, from the *COBE*–FIRAS experiment with resolution of about 7 degrees (Wright et al. 1991), from the map at 170 GHz with resolution of 3.8 degrees produced by the MIT survey (Ganga et al. 1993; Meyer et al. 1991).

About dust emission spectrum and fluctuations additional information is expected from the analysis of the far–IR *COBE*–DIRBE maps (Hauser 1993).

Wright et al. (1991) presented their results in terms of a product of a function of position times a function of frequency:

$$I_G(l, b, \nu) = G(l, b)g(\nu). \tag{5}$$

The best fit of the frequency function turned out to be:

$$g(\nu) \approx 2.2 \times 10^{-4} \left(\nu/900GHz\right)^2 \times \left[B_\nu(20.4) + 6.7B_\nu(4.77)\right]. \tag{6}$$

where B_ν represents the Planck function. As for dust anisotropies, Gautier et al. (1992) studied the angular power spectrum of the IRAS 100μm maps and concluded that dust fluctuations decrease with angular scale according to a power low with an index ~ 0.45.

2.2.1 Fluctuations of the galactic emission at sub–degree angular scales

The level of the expected galactic noise can be predicted from the already available data. Brandt et al. (1993), starting from the radio maps at 408 and 1420 MHz and using all other available information (e.g. spectral indexes, magnetic fields etc.), were able to pick out 50 high galactic latitude regions of 10×10 degrees in which synchrotron and dust emission at 31 and 100 GHz are rather smooth on angular scales of ~ 1 degree. Actually, in these regions the rms intensity variations are less than 2.1×10^{-4} MJy/sr with a total intensity ranging from 6 to 10 times the rms. Figure 1 shows that for these regions

the expected synchrotron rms variations (dotted line) yield $(\Delta T/T)_{rms} \lesssim 3 \times 10^{-6}$ at frequencies $\nu \gtrsim 40$ GHz. Therefore, in the frequency range $50 \lesssim \nu \lesssim 600$ GHz, the synchrotron intensity fluctuations are significantly smaller than CBR fluctuations.

Similar conclusions can be drawn for the case of the free–free emission. Using the free–free to H_α and N^+ emission ratio (Wright et al. 1991; Reynolds 1992; Bennett et al. 1992) it is possible to infer a generous estimate of 1.2×10^{-3} MJy/sr at $\nu = 53$ GHz for the total free–free emission at $\mid b \mid \geq 40$ (which corresponds to $\sim 15,000$ square degrees). From Figure 2 of Reynolds (1992) rms variations of about 30% of the total emission can be estimated. Figure 1 shows that the corresponding $\Delta T/T$ level (short–dashed line) adds a small contribution to the expected primeval CBR fluctuations at frequencies $50 \lesssim \nu \lesssim 500$ GHz.

At still higher frequencies, due to rapid decrease of the CBR intensity, the radio emissions would provide again detectable anisotropies but they are completely swamped by the anisotropies produced by dust emissions (see Figure 1).

The *COBE*–FIRAS dust map (Wright et al. 1991) shows that a non negligible portion of the sky exhibits rather low brightness at sub–mm frequencies. Taking the brightness at 100 μm as a reference, 10% of the sky shows a brightness less than 1.5 MJy/sr. Dust emission can be indirectly derived from HI maps (see e.g. Stark et al. 1992). As reported by Lockman et al. (1986) about 8% of the sky has HI column densities $N_H \lesssim 1.5 \times 10^{20}\ cm^{-2}$. Using the correlation between 100 μm and HI emission derived by Boulanger & Perault (1988) such column densities would correspond to sky brightness less than 1.3 MJy/sr at 100 μm. The distribution of the column densities is rapidly increasing from $N_H \sim 5 \times 10^{19}$, which is the lowest detected value in the sky. No more than 1% of the sky exhibits $N_H \leq 1 \times 10^{20}$. Extremely–low emission regions, such as the Lockman Hole or the South Pole Hole or the GUM area, are rare (Lockman et al. 1986).

It is worth noticing that areas of the sky with relatively low HI column densities are also remarkably smooth, with a dispersion $\sigma/\langle N_H \rangle \lesssim 0.15$ (Lockman et al. 1986).

In Figure 1 we reported the fluctuations generated by the galactic dust based on the assumption that the rms variations amount to 100% of the total emission in the lowest emission regions, i.e. 0.4 MJy/sr at 100 μm (see above), a level which is well within the capabilities of a high sensitivity survey for dust mapping in the sub–mm range. It is apparent that the predicted dust fluctuations are rather small $(\Delta T/T)_{rms} \lesssim 5 \times 10^{-6}$ for frequencies $\nu \lesssim 300$ GHz.

At high enough galactic latitude ($\mid b \mid \ \gtrsim 40$) subtraction of the galactic emission is on average required with relative accuracy levels of $\sim 20\%$ of the signal in order to get galactic noise below several μK in the frequency range $30 \lesssim \nu \lesssim 300$ GHz. To reach this goal large sky coverage, a few μK sensitivity and wide frequency range are needed.

2.3 Extragalactic emissions

A short but complete report on source confusion due to extragalactic point sources can be found in Toffolatti et al. (1994). Their results show that extragalactic point sources are expected to produce $(\Delta T/T)_{rms} \lesssim 2\times10^{-6}$ at angular scales of interest here ($10' \lesssim \theta \lesssim 30'$) in the frequency range $50 \lesssim \nu \lesssim 300$ GHz (see Figure 2). As previously discussed by Franceschini et al. (1989), the main source of uncertainty in predicting the confusion noise due to extragalactic sources is the very large frequency extrapolation of the source counts, which are currently known only at cm wavelengths in the radio and at 60 μm in the far–IR.

Referring to Franceschini et al. (1989) we can say that the present predictions should be accurate within $\approx 30\%$ for $\lambda \gtrsim 1$ cm and to within a factor of $\sim$2 down to $\lambda \approx$ a few millimeters. In the sub–mm wavelength range, where the confusion noise is dominated by dust emission, the two adopted models give an appropriate estimate of the uncertainty in the predictions (see caption to Figure 2). The limits reported in Figure 2 can be achieved eliminating 5σ sources (see Franceschini et al., 1989 for more details). If source surveys were available with limiting fluxes fainter than 5σ, then the source contribution can be lowered and the optimum frequency range widens. Fluctuations generated by galaxy clusters through the S–Z effect provide foreground noise in experiments designed to map the intrinsic CBR anisotropy. Recently Bond & Myers (1993) have investigated the formation and evolution of galaxy clusters in the frame of CDM models. Indeed they considered not only the *standard* CDM model, but also other alternatives of structure formation within the inflationary scheme. They have produced the angular power spectra of the S–Z effect produced by various structure formation models. Their results show that the integrated S–Z effect would produce fluctuations at level of 10% of the primary $\Delta T/T$ at scales $> 10'$. Thus S–Z effect would not affect the detection of primordial fluctuations on larger scales. Ceballos & Barcons (1994) using a parameterization of the X–ray luminosity function of clusters and a simple model for its evolution were able to show that the average Compton $< y >$ parameter is always $< 10^{-6}$. Similar, albeit a little higher, values are also found by Markevitch et al. (1992), who combined X–ray measurements of the luminosity distributions of relatively nearby clusters ($z < 0.2$) with simple models of structure formation and cluster evolution.

Ceballos & Barcons (1994) also show that the anisotropies imprinted at arcmin scales are dominated by the hottest undetected objects and that they are negligible ($(\Delta T/T) \lesssim 10^{-6}$) at $\lambda \gtrsim 1$ mm while becoming more important at shorter wavelengths ($(\Delta T/T) \sim 10^{-5}$ at $\lambda \simeq 0.3$ mm). Anyway, since most clusters will produce an isolated and detectable feature in the sky maps they could be subtracted out leaving only less bright objects producing negligible background noise. For beamsizes $\sim$ 10 arcmin confusion will be more relevant and only the hottest clusters ($T_{gas} \gtrsim 7$ keV) will be detectable. Even in that case, the remaining undetected objects will produce negligible sky noise. On the other hand, Bond & Myers (1993) pointed out that the S–Z effect

generates a significant non–gaussian tail in $\Delta T/T$ distributions on scales of about $10'$ that could be probed provided that large enough statistics are available. A coverage of several 10^4 pixels is required to get significant results (see Bond & Myers, 1993 for more details).

Due to the nature of the S–Z effect the deflections are negative for frequencies $\nu \lesssim 200$ GHz and positive at higher frequencies. Thus experiments in the appropriate frequency range might test the non-gaussianity generated by S–Z effect.

3. REMARKS ON EXPERIMENTAL APPROACHES

The different environment conditions which characterize ground-based, balloon-borne and space experiments strongly affect the choice of the measuring technique to be implemented, and determine the limitations and quality of the expected results. Table I summarizes the main aspects discussed here.

3.1 Frequencies and techniques

As mentioned, ground based measurements are allowed only in few fixed atmospheric windows downwards of 90 GHz, and only few independent frequency bands can be covered. In this regime one can take advantage of the new generation, high-quality, coherent detectors, such as SIS (Superconductor–Insulator–Superconductor) (see Pan et al., 1989) or, even better, HEMT (High Electron Mobility Transistors) radiometers (Pospieszalski, 1993; Pospieszalski et al., 1993). These devices have very low noise figures, especially when cryogenically cooled, and have proved suitable for these experiments (see e.g. Meinhold et al., 1993).

In the case of balloon experiments the effects of the atmosphere are strongly reduced (although not suppressed) so that high–frequency measurements ($100 < \nu < 900$ GHz) can be performed. Very sensitive cryogenically cooled bolometers are the typical solution for balloon–borne experiments (see Figure 3). The high sensitivity is achieved with broad–band channels which, however, decrease the power in the spectral separation (typically the 3-4 band allowed are adjacent to each other).

For a space mission, in principle, the whole frequency range is available with no limitations other than the unavoidable galactic and extragalactic emission (see §2). The European Space Agency COBRAS/SAMBA project (ESA M3 Assessment Study Results, Summary Reports SCI(94)9, May 1994) takes full advantage of this possibility proposing measurements in the frequency range $30 < \nu < 900$ GHz by integrating radio– and bolometric detectors at the focal plane of a ~ 1.5 m aperture off–axis telescope on a payload in a far–Earth orbit. Passively cooled receivers with ultra–low noise HEMT preamplifiers can cover the low frequency interval up to ~ 130 GHz, while bolometers cooled down to ~ 0.1 K provide extremely sensitive detectors in the range

100–900 GHz. The two different detection techniques can easily exploit 7-8 observing bands, with the possibility of frequency overlap close to 120 GHz. This, together with large sky coverage, allows strong control over systematic errors by a very powerful frequency/foreground/technique crosscheck of the maps.

3.2 Contamination from Earth radiation

Sub–degree anisotropy experiments carried out from the ground or near the Earth's surface require very efficient rejection of off-axis radiation to avoid comtamination from the unwanted emission from the Earth. The level of rejection required becomes increasingly severe when the goal sensitivity is pushed to more and more ambitious limits. From balloon altitudes, since the distance of the gondola from the Earth is negligible compared to the Earth radius, the sidelobe and straylight rejection required is of the same order as for ground-based experiments.

If one imposes the total ground contribution to fall below significance level, a ground–based or balloon experiment with angular resolution $\sim 30'$ and sensitivity $\Delta T/T \sim 10^{-6}$ implyes a rejection factor at large angles as high as 10^{12} to 10^{13}. However, since the measurement is contaminated by *variations* of the ground radiation spill–over rather than its *absolute value*, this factor should be regarded as a conservative limit for a worse–case scenario. In principle, significantly less stringent rejection limits (probably by a factor ~ 100) can be acceptable provided that the experiment does not require movements, relative to the Earth, of the instrument parts which control the amount of ground radiation adding to the measured signal. Typically, this is the case of ground–based experiments, which also have the advantage of possible use of extended reflective gound screens to minimise the signal.

While meaningful measurements from the ground or from balloons have been performed with accuracies $\Delta T/T \sim 10^{-5}$, Earth radiation contamination has always been a major concern. Pushing the sensitivity to the next order of magnitude is likely to be very problematic, particularly with the objective of extended sky coverage.

A space mission from a low–Earth orbit would only marginally relax this critical requirement, since the Earth would still cover about 1/4 of the total solid angle. For instance, microwave emission from the Earth has been a serious concern in the design and systematic error analysis of the *COBE*–DMR experiment, even at the relatively broad angular resolution (7°) of its antennas (Kogut et al., 1992). From the *COBE* 900 km circular orbit, the Earth is a circular source with angular diameter 122° and minimum temperature 285 K. Upper limits to the antenna temperature of the Earth signal contribution to the DMR 2–years data are at level 25–60 μK (95% confidence level), (Bennett et al., 1994). It is clear that rejection of Earth radiation is a challenge to low–Earth orbit experiments aiming to reach sensitivities a factor ~ 10 better than *COBE*–DMR with beam areas smaller by a factor of $\sim$100 to $\sim$1000.

Only by moving the payload to a far–Earth orbit, like Moon–Earth libration point L5 ($\sim 400,000$ km, i.e. the orbit presently selected for COBRAS/SAMBA), or Sun–Earth libration point L2 ($\sim 1,500,000$ km, i.e. the orbit proposed for the PSI mission, and also considered for COBRAS/SAMBA), the Earth's solid angle is greatly reduced, thus decreasing by the same factor the required rejection. In the most conservative approach, the rejection requirement drops by four order of magnitude (10^8 to 10^9), and becomes comparable to that needed to suppress Sun radiation. This rejection level can be obtained with careful, though conventional design of the optics and shielding.

An additional advantage of a deep–space environment concerns the thermal conditions ($T \sim 100$ K, stability $\simeq 0.1$ K/few weeks) which are ideal for passively cooled, long-lifetime experiments. For example, the COBRAS/SAMBA Low Frequency Instrument (LFI) is a multifrequency radiometer array designed to function for up to four years exploiting the passive cooling technique, although the scientific objective will be reached within the nominal 2 years mission lifetime.

3.3 Experimental configurations

The main design considerations are driven by the need to obtain the nominal experiment performances (resolution, sensitivity, sky coverage, window function, etc.), with minimum and well–controlled potential systematic effects.

In order to achieve angular resolution < 1 deg in the frequency range allowed by galactic and extragalactic foregrounds ($30 \lesssim \nu \lesssim 300$ GHz) large (~ 1 m) telescopes are needed, which properly redirect in the sky the feed beam pattern. Clear aperture, oversized optics, either Gregorian or Cassegrain, are used to minimize diffraction and spillover effects (e.g. Meinhold et al., 1993; Fisher et al., 1992).

In most sub–degree anisotropy experiments, a moving (rotating or nutating) subreflector provides the beam–switching pattern necessary to efficiently subtract instrumental and atmospheric drifts. The Tenerife triple–beam switch strategy, suitable for their larger (~ 8 deg) angular scale, has proved particularly effective for the subtraction of slow atmospheric drifts (Davies et al. 1992). In general, moving the subreflector or other reflective parts is a source of concern for potential systematic effects, such as possible modulation of signals from the Earth (or the balloon) diffracted in the beam or sidelobes by the instrument structure. In general, the rejection and control of systematic errors imposed by a sub–degree measurement at sensitivity $\Delta T/T \approx 10^{-6}$ requires an environment and viewing field extremely free from local contamination. An eloquent example of the critical level reached by traditional balloon or ground based designs for these experiments is the futuristic concept proposed for TopHat (Cheng 1994).

The window function of the experiment, which is determined by the instrument beam and sky scanning technique, selects the angular range at which the measurements are most sensitive. Typical beam switch experiments have window functions W_l peaking

in a relatively narrow range of the corresponding scales of the primordial power spectrum (Bond et al. 1991). Most performed measurements have been designed to sparsely sample the autocorrelation function at a fixed angular scale; on the other hand, to obtain a model–free reconstruction of the power spectrum one needs a filter function W_l nearly constant over a range of angular scales as wide as possible. This is the characteristic of an imaging observation (Readhead and Lawrence 1992), where several widely different angular scales are simultaneously probed. Interferometry and arrays of radiometers or bolometers, with proper sky scanning strategy, can both in principle obtain images of large areas of the sky with the required sensitivity.

4. DISCUSSION

Large sky coverage and high final sensitivity are fundamental requirements for measurements of sub–degree CBR anisotropy aiming to cast light on the nature and the origin of the fluctuations from which the present stuctures in the universe have developed. Several lines of argument point to quantify the sky coverage requirement to at least 10,000–15,000 square degrees or, equivalently, about 30% of the sky and the sensitivity to $\Delta T/T \approx 10^{-6}$. For the case of an imaging experiment, the large number of pixels would permit to precisely reconstruct the radiation power spectrum from the beam angular resolution up to the largest scale allowed by the sky sampling. In the case of the COBRAS/SAMBA experiment this will be obtained in the angular range from $10'$ up to the *COBE*–DMR angular resolution. Large and high quality statistics would also make possible to discuss the contribution of the galaxy clusters to the fluctuations distribution, with the aim of discriminating among various possible histories of their evolution.

Are these goals reachable with ground–based or balloon–borne experiments?

As for ground–based experiments three major difficulties have to be solved that are somewhat connected: atmospheric noise, galactic emission removal and sky coverage.

Since above 25 GHz the atmospheric signal at the best ground–based sites (e.g. at the Amundsen–Scott South Pole Station) ranges from ~ 3.5 to 9 K, we need to eliminate the atmospheric noise to a level $\lesssim 10^{-6}$ of the signal. This is a factor of 3–4 smaller than the performances of current experiments which already run into the atmospheric limit (Gaier et al. 1992). In addition to the well known water vapor variations, high and low pressure regions in the atmosphere are likely to determine significant O_2 fluctuations which require very long integration to be averaged out (Meinhold et al. 1993).

The Galaxy emission removal is strictly related to the problem of the atmospheric noise and observing frequency. In general precise subtraction of the galactic contribution is very difficult with observations confined in a small frequency range and in the presence of atmospheric noise (Brandt et al. 1993). From Figure 1 it is clear that even in the

regions of the sky in which the emission is low, subtraction of the galactic signal is needed at frequencies $\nu \lesssim 40$. Unfortunately, the possible observing frequencies from the ground are restricted by the presence of the strong H_2O line at 22.2 GHz and the oxygen band peaking at about 60 GHz (see e.g. Danese & Partridge 1989). Thus atmospheric noise and the limited range of available frequencies conspire against precise removal of the Galaxy contribution. In order to minimize galactic foreground emissions, measurements have been attempted in the atmospheric window near $\nu \simeq 90$ GHz. However at this frequency the atmospheric antenna temperature is $\gtrsim 9$ K even at the Amundsen–Scott South Pole Station.

Attempts of obtaining large sky coverage from the ground face additional problems. Because both the total contribution and atmospheric fluctuations strongly increase away from the zenith, ground–based observations are confined in regions around the zenith. This constraint also limits the possibility of chosing low–foreground sky patches for the observations.

While it is conceivable that detection of anisotropies with amplitude $\Delta T/T \sim$ 3–4×10^{-5} can be obtained from the ground at 3–4 σ level, nonetheless it is clear that the large sky coverage required by the arguments presented in §1 is not obtainable.

As for balloon–borne experiments the main problem is the sky coverage, which is strongly limited by the short flight time. Even using very sensitive bolometers such as those foreseen for the upgraded MAX experiment, it seems possible to get only about 50–100 pixels per flight. TopHat and similar experiments are presently under study, with the aim of minimizing the instrumental systematics. Polar long–duration flights are also foreseen. On the other hand assuming very optimistically that these experiments successfully flew 4–5 times in the next 10 years, they would produce data for no more than 500–1000 pixels (see, e.g., Cheng 1994). As a consequence the large coverage needed to answer the fundamental cosmological questions are well beyond the capabilities of balloon–borne experiments flying in the next 10 years.

In smaller sky patches high-quality balloon measurements are possible, most likely at high (> 90 GHz) frequencies. However, as pointed out in §3, balloon measurements at sensitivities $\Delta T/T \sim 10^{-6}$ will have to suppress earth radiation with an efficiency 3 to 4 order of magnitude more than what can be presently achieved. Moreover, the residual atmospheric contamination and the small coverage enhance the problem of the Galaxy emission removal. As mentioned before, the Galaxy subtraction problem is alleviated only when observing the *few low emission* regions of the sky. On the other hand, the access to these regions from balloons during long–duration flights might be difficult.

A further point to take into account is that there is no substitute for *imaging* observations (Readhead & Lawrence 1992). Indeed only by imaging the CBR anisotropies the power spectrum can be analysed in a model–independent way. While single or double switching procedures used in balloon–borne experiments can only sparsely sample

the power spectrum, imaging free from systematic errors is obtainable only with a space mission.

In conclusion accurate studies of the CBR anisotropy power spectrum from $10'$ to degree angular scales are possible with the data obtainable only with a space mission in a far-Earth orbit. In particular the joint COBRAS/SAMBA mission has many exciting characteristics:

- it would cover *all* the frequency range ($50 < \nu < 300$ GHz) and *all* the sky regions (basically $b \gtrsim \mid 30 \mid$ i.e. $\sim 1/2$ of the entire sky) for which the subtraction of the foregrounds would not give troubles for high sensitivity all sky surveys from space; this would results in negligible statistical errors in the power spectrum reconstruction up to a few degrees;
- it will be placed in a far–Earth orbit ($\sim$ 400,000 km from the Earth), dramatically decreasing the problem of the sidelobe and straylight rejection;
- at low frequencies (observations performed by radiometers) the galactic noise is generated by synchrotron and free–free emission, while at the highest frequencies of the experiment (observations performed by bolometers) dust emission dominates. Indeed this mission would get 5–6 maps of the CBR fluctuations with high angular resolution on more than half of the sky and in the best frequency window, where galactic and extragalactic emissions are at their minimum value, as it is apparent from Figure 1 and 2. This would offer the opportunity of a fundamental cross-check of the results;
- at three frequencies (31, 53 and 90 GHz) the product maps can be straightforwardly compared with those of $COBE$–DMR;
- although confined to the tails of the fluctuation distributions, nevertheless the S–Z effect in galaxy clusters produce different features (positive and negative tails respectively) on the fluctuations distributions at different COBRAS/SAMBA frequencies, allowing a clear separation of the effect from other possible sources of non–gaussianity. In this respect it will be extremely interesting to compare the COBRAS/SAMBA maps to the ROSAT all–sky survey of galaxy clusters.

5. CONCLUSIONS

A wealth of information about the history of the Universe from the very beginning to the present structure is imprinted in the CBR anisotropy. The observations and the theoretical work so far done have spectacularly increased our knowledge in the field and have stimulated a number of observational projects for the next decade. The proposed experiments will be carried out from ground, balloon and space.

The above discussion has shown that only a precise and accurate reconstruction of

the CBR power spectrum on angular scales ranging from several arcminutes to several degrees will produce an exceptional and possibly decisive step towards the understanding the physical state of the very early universe and the evolution to its present structure, with enormous impact on particle physics. Large sky coverage and precise foreground subtraction (which indeed are deeply interrelated) are mandatory to achieve this goal. Only by imaging CBR anisotropies over a large fraction of the sky we will obtain a model-independent, precise determination of the radiation power spectrum.

Although it is apparent that much can be learnt from ground–based and balloon–borne experiments, nevertheless they are not suitable to produce extended maps of the sky to the required precision in the next ten years or so. Only from space a properly designed experiment can image the sky with the needed precision and coverage. The frequency range, sensitivity and orbit proposed by the COBRAS/SAMBA project will allow to produce near–all–sky maps with very small systematic errors, which will be one of the most fundamental data set in cosmology and astroparticle physics.

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FIGURE CAPTIONS

Figure 1. Estimated fluctuation levels of galactic emission components at ~ 0.5 degree angular scale in high galactic latitude sky areas, $|b| \geq 40$ (in terms of the thermodynamic temperature $\Delta T/T$). The horyzonthal continuous line indicates a constant level $\Delta T/T = 10^{-5}$. The dotted line represents the fluctuations due to the synchrotron emission in regions where the rms intensity at 100 GHz is less than 2.1×10^{-4} MJy/sr (see text). As for the free–free emission, the short–dashed line refers to a $\Delta T/T$ level estimated assuming an rms intensity fluctuations of about 30% of the total emission (see §2.2.1). The continuous line refers to fluctuations generated by the galactic dust based on the assumption that the rms variations amount to 100% of the emission in the *coldest* areas of the sky, i.e. 0.5 MJy/sr at 100 μm (see text); we have also reported the contribution to the total $\Delta T/T$ level given by the two dust components ("cold": dot–long–dashed; "warm": dot–short–dashed) as modelled by Wright et al. (1991) (see §2.2 for more details).

Figure 2. Estimated fluctuation levels due to extragalactic point sources (in terms of the thermodynamic temperature $\Delta T/T$). The plotted curves refer to a source detection limit $x_c = 5\sigma$ and to different models for the evolution of the cold dust. The higher $\Delta T/T$ level corresponds to the model by Franceschini et al. (1988) assuming strong cosmological evolution of the most luminous far–IR selected sources, while the lower one refers to a moderate cosmological evolution of both late– and early–type galaxies (Franceschini et al., 1994). Both models give integrated intensities $I(\nu)$ still compatible with the recent *COBE* FIRAS upper limits on the CBR residuals in the sub–mm domain (Mather et al., 1993; Wright et al. 1993) but the higher one is close to infringe the FIRAS limits. The frequency channels foreseen for the COBRAS/SAMBA experiment, 31.5, 53, 90, 125, 230, 375 and 670 GHz, are also indicated by the dotted vertical lines.

Figure 3. Comparison of the spectral coverage of some anisotropy experiments recently performed or under study. Dark squares represent bands covered with radiometric techniques, while boxes are bolometric passbands. For details on the single experiments see, e.g., UCSB-SP91: Schuster et al. 1994; Python: Dragovan et al. 1994; Tenerife: Hancock et al. 1994; MAX: Gundersen et al. 1993; ARGO: De Bernardis et al. 1994; TopHat: Cheng 1994; *COBE*-DMR: Smoot et al. 1992; COBRAS/SAMBA: Mandolesi et al. 1994. The Tenerife and *COBE*-DMR measurements have been performed at $\sim 5°$ and $7°$ angular resolution whereas all the other experiments are at degree or sub–degree angular scale.

TABLE I. Space vs. Ground and Balloon Experiments

SCIENTIFIC OBJECTIVES: extensive imaging (i.e., more than $\sim 40\%$) of the sky (in particular the portion at $|b| > 40^o$) with a sensitivity $\Delta T/T \simeq 3 \times 10^{-6}$ per pixel and angular resolution $\sim 10'$-$30'$.

	GROUND	**BALLOON**	**SPACE**
FREQUENCY			
freq. range	10-18,28-40,90 GHz	10-900 GHz	10-900 GHz
technique	radiometers	bolometers and/or radiometers	both
ENVIRONMENT			
thermal variability	several K/day	few K/day	~ 0.1 K/few weeks (L5)
diffraction, reflection emission	moving parts on ground	balloon, gondola, chopping-spinning	payload spacecraft
required sidelobe rejection (Earth)	10^{13}	10^{13}	10^{9} (L5)
DATA			
$T_{\rm atm}/\Delta T_{\rm CMB}$	$\geq 10^6$	$\sim 10^3$	0
Data rejected for atmospheric fluctuations	$\sim 70\%$	$\sim 10\%$	None
actual integration time (per year)	$\sim$ 10-20%	$\sim$ 3-4%	$\geq 90\%$
overall efficiency	low	medium	very high
FOREGROUNDS			
Galactic foreground subtraction	hampered by atmospheric fluct., limited sky coverage, small freq. range	reliable only with many frequencies and many flights	highly reliable (multifreq. obs. + sky coverage)
extragalactic sources	external surveys	external surveys	multifreq. obs. + external surveys
SKY COVERAGE			
pixels per year at $\Delta T/T \sim 3 \times 10^{-6}$ (per frequency)	$\sim$ 50-200 pixels	~ 1000 pixels	$\sim 100,000$ pixels
% of all sky	0.1%	0.6%	$\simeq 60\%$
limiting factors	data efficiency, accessibility, foreground subtrac.	integration time, accessibility, foreground subtrac.	instrument sensitivity, mission lifetime

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